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VISITOR-CENTERED PLANNING, STRATEGY, AND EVALUATION

# XR in Museums

## A Review of the Current State of the Field

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This paper was funded by the NSF-funded project:
Re-Living Paleontology: Studying How Augmented Reality Immersion and Interaction Impact Engagement and Communicating Science to the Public DRL-1810984

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April 20, 2023

## Introduction and Project Background

> Virtual reality is a magical realm in which our human perceptions of time and space are suspended. In virtual reality, nothing is too small, too big, too fast, too slow, too distant, or too long ago to be appreciated. *-Vivian Trakinski, Director of Science Visualization at American Museum of Natural History (Hayden, 2019)*

This paper is intended to serve as a robust review of the current state of the field of augmented reality and virtual reality as applied within museums. We have restricted our focus to visitor-facing applications, rather than those for staff or exhibition design. Similarly, we have restricted this review to augmented reality (AR) and virtual reality (VR) applications, known collectively under the umbrella term extended reality (XR), rather than the overlapping applications in image recognition, projection mapping, and gestural response.

Our goal is to provide the museum professional with synthesized research on where XR is most effective within a museum setting and what impact XR might have on the visitor experience, along with sample projects and citations. Based on this review, a museum professional will have better insight into whether and where XR applications may be useful within their institution.

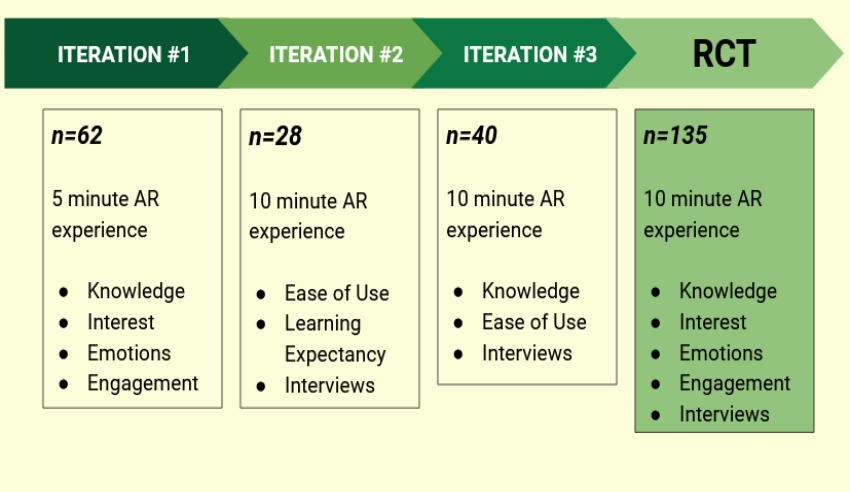
### The La Brea AISL Grant

This paper was funded via a project at the La Brea Tar Pits about learning through an AR experience. With the support of a National Science Foundation- Advancing Informal STEM Learning (AISL) research grant, researchers from University of Southern California's Rossier School of Education (USC) and Institute for Creative Technologies joined with staff from the Natural History Museum of Los Angeles (NHM) on a project titled *Re-Living Paleontology* or (more informally) *Tar AR*.

The USC team chose to explore science learning through XR at La Brea Tar Pits due to its unique capacity for delivering science learning with the on-site 'tar' and its treasures, displayed directly next to the pits. The NHM/USC team wrote of the project: "Still under excavation, the Tar Pits are the only active paleontological dig site located within a major metropolis and provide a unique opportunity to show the public the entire process of paleontology from excavation and preparation to research and display" (Davis et al., 2022). Even with this physically close connection between discovery, research, and museum learning, visitors can come away from the Pits and Museum with some misconceptions about the site, for example: "All the fossils are from big animals that are extinct today," "The scientists are all actors and the lab is just for show," or "L.A. was covered with ice."

Prescribing to the popular belief that AR is "the next frontier" for museums (Pardes, 2018), the USC team saw an opportunity to determine whether AR could correct these misconceptions. Watching accurately-animated Ice Age animals moving through the public site was expected to increase understanding of what that land's history looked like. The goal of the project was to determine the efficacy of AR in museum learning, exploring whether visitors learn better with AR compared to traditional museum didactics. Three conditions–an AR headset experience, an AR handheld (phone) experience, and a two-dimensional didactic sign–were tested at two sites: Pit 91 and "The Field," a public park that is surrounded by the bubbling asphalt, excavations, and the La Brea Museum.

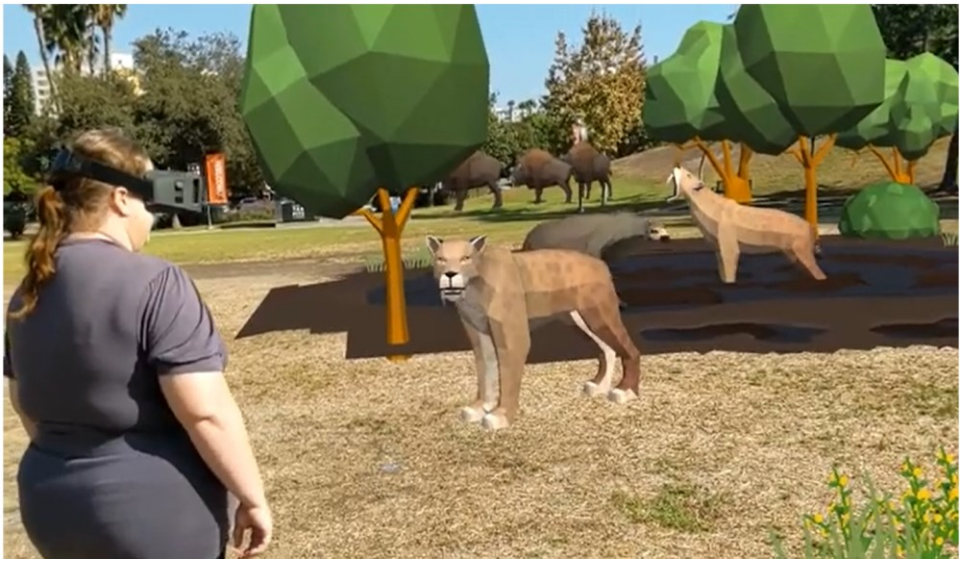
Four studies were performed: Iterations 1 through 3, and a Randomized Controlled Trial (RCT):




(Nye at al., 2023)

Though visitors' learning increased in each condition, data resulted in little difference between the learning gains with AR and with the more traditional, didactic sign. Other benefits to AR were noted, however, raising new questions about the impacts of XR on museum audiences. Is XR still valuable to museums, if lower-cost and -maintenance tools teach just as well?

(Nye et al., 2023)



(Nye et al., 2023)

**Core Questions & Methodology**

Our recent work on the NSF-funded grant for *Tar AR* gave us the chance to compile museum-based XR projects and complete interviews with museum technology experts. This review looked at XR components which are most successful in improving the visitors' experience. The core questions considered for the review were (1) In what contexts has AR/VR been most successful in heightening the visitor experience?, and (2) What are the possible outcomes from using XR in museums? We used three approaches–a project review, expert interviews, and a literature review–to gather evidence and insight for this paper.

We conducted the project review from September to November of 2022, resulting in a list of 72 projects that used AR and/or VR in or with museums since 2018 (Appendix A). We first located these projects through emails and meetings with experts within the field, then looked for other projects which were cited in those write-ups, while also reviewing projects that had received grant funding through AISL. Colleagues regularly recommended examples outside the museum field, yet many of those use cases were highly different, and transference from outside the field seemed fairly rare.

Concurrently with our project review, we interviewed 11 experts who work in, or work adjacent to, the field of museum technology (Appendix B). These experts were either recommended to us by colleagues during the project review, or were already experts we had worked with. Interviews took place mostly over Zoom from September through December of 2022, with some phone calls and one in-person meeting. While our interviews are undoubtedly biased by our knowledge of XR projects, it is our hope the literature review helps enlarge that view, creating a larger sample to examine.

The literature review resulted in a list of 29 papers that explore uses, impacts, and outcomes of XR in or with museums, mostly since 2018 (Appendix C). Some of these projects are still in development and have not yet reached audiences; others are completed and no longer available. We focused solely on projects that included AR and/or VR, without including those with other media sometimes grouped in the same category of XR. Projection mapping, immersive screens, and image recognition, for example, were not included in the focus of this report.

## In What Contexts Has AR/VR Been Most Successful in Heightening the Visitor Experience?

Over the last decade, there have been hundreds, if not thousands, of AR and VR projects in museums. The *Tar AR* project at La Brea Tar Pits that serves as the genesis of this review was a research-based grant focused on different form factors of AR and VR and different levels of immersion in order to determine what elements of an AR or VR experience facilitate science learning and visitor interest and enjoyment. The central questions were (1) Do visitors actually learn better with AR compared to a 'normal' museum exhibit?, and (2) Is more immersive and interactive AR better than simple, smartphone-based AR? As one museum professional stated, "Why should I go through all this time and expense for an AR/VR project if I can achieve the same effect from a Pepper's Ghost interactive?"[1]

The qualitative analysis from *Tar AR* on participant learning surfaces several ideas. First, the surprise factor was a revision of visitors' initial assumptions, and that revision led to deeper understanding of the fossil evidence (Herrick et al., 2021). The research team found that participants had significantly fewer misconceptions at post-test than at pre-test (Herrick et al., 2021). Participants also reported higher levels of interest in science content than AR technology and discriminated between emotions they experienced with regard to science content and AR technology (Herrick et al., 2021). Feelings of curiosity predicted knowledge revision and interest in both science content and AR technology (Kennedy et al., 2021). Scores on content knowledge in the post-test were not significantly different between the different conditions—there was no difference in learning between the sign and the AR conditions recorded.

The findings from this research are situated within a particular context—an outdoor, science-based experience aimed at dispelling misconceptions surrounding the Tar Pits and fossilization. The goal of the experience was to increase interest in the science content, increase in specific knowledge, and prompt visitors to consider how scientific processes work. Other AR and VR applications vary; in some, the goal may be to encourage visitor participation, or to conjure an emotional response. In considering these findings, we needed more information to determine whether these results might be generalizable to other subject matters, settings, and goals.

[1] Pepper's Ghost refers to an illusion technique involving glass and a hidden room or area to give the effect of a person or object appearing where they are not. The technique dates from the 1860s and is still in use today in museums, theater performances, amusement parks, and rock concerts.

This research spurred our team to look at other museum-based projects to compile under what conditions AR and VR components are most successful in increasing the visitors' experience. In our interviews, experts expressed that AR was particularly successful in six contexts:

1. Outdoor applications,
2. Timeline shifts,
3. History museums and historical sites,
4. Understanding or changing scale,
5. Inaccessible sites made available, and
6. Representing absence.

Of course, AR-based projects could be successful beyond these contexts, but as these six were repeatedly identified, we prioritized them in this report. Examples below highlight projects used thus.

### 1. Outdoor Applications

In locations where other types of storytelling are constrained, XR can be particularly advantageous, especially outdoors. Larry Swiader, Chief Digital Officer at American Battlefield Trust, described projects in which his team was unable to install any other exhibition components in the spaces they were interpreting, even a sign. Their AR app allowed visitors to have interpretative content where that content is missing from Revolutionary and Civil War sites. For *Battlefields and Streets*, AR was the sole component for interpretation. Swiader explained why during our interview:

> For our projects, I feel like the use case is much more straightforward because we deal with battlefield parks that tend to be empty of information. And when the situation is perfect for a visitor to a battlefield park, they may walk it on their own or with some company, or they may choose to have a guide with them that can bring to life the stories that need to be brought to life because you can't see them in front of you. There's no wall text for you in a battlefield. But more and more, because of National Park Service budgets, there are fewer and fewer guides, people, or rangers to give those tours. So that, in combination with the fact that you're dealing with empty spaces anyway, makes augmented reality, where we're putting something in front of you that is not there but is a part of the history and the understanding of the history of that place, it makes sense. It's a use case that immediately makes sense.

In a more contemporary setting, a research team based out of Penn State University developed a mobile AR app for families to use in a children's garden cave within an arboretum. The app focused on "water-rock interactions" with the goal of enticing rural families to earth science learning (Zimmerman et al., 2020). The 2020 study concluded that the app increased family learning interactions, with small knowledge gains (Zimmerman et al., 2020). While this is not yet a publicly available app, research continues and is pointing towards deeper connection to outdoor informal education sites, and social learning, via AR.

## 2. Timeline Shift

AR and VR were both useful in supporting visitors' ability to experience different points in time, serving as a timeline teleporter. In the *Tar AR* project, visitors were transported tens of thousands of years back in order to better understand how the La Brea Tar Pits entrapped plants and animals. In another example, the NEH-funded *Chicago 00* World's Fair experience, forty-two percent of the audience felt that they were "there," personally, as one of the people in the narrative (HG&Co, 2020).

Timeline shifts like those above were common in history museums and historical sites, but also appeared in art and science museums. Using photogrammetric scans of Lee Krasner's and Jackson Pollock's paintings, visitors to the Pollock-Krasner House and Study Center, can see how the house/studio and its art appeared in the 1940s and 50s, before the artworks were sold (Owen, 2021). One visitor commented, "The virtual reality program made you feel like you were right there when he made the paintings. There's no greater way to connect with the artist unless you visited him in the studio when he made them." (Owen, 2021).

*Revealing Krishna: Journey to Cambodia's Sacred Mountain* at the Cleveland Museum of Art (CMA), in partnership with The National Museum of Cambodia, explored the provenance of a 1500-year-old Cambodian statue of the Hindu god Krishna (Microsoft, 2022). Using HoloLens headsets, audiences experienced the statue's original environment in Phnom Da, in Brussels where it resided in pieces in the 1920s, and in incomplete conservation in an American museum (Microsoft, 2022). The XR tour had the highest overall experience rating of recent exhibitions (LaFrance & Gutow, 2022). One visitor commented: "Very thorough explanation of the context of these statues & their importance over time. Loved the holograms!" (LaFrance & Gutow, 2022).

## 3. History Museums and Historical Sites

History museums and historical sites were frequent hosts for XR projects in our review, taking advantage of the capabilities of timeline shift and outdoor feasibility. Out of the 72 XR projects, 25 (roughly 35%) dealt with human history and culture. Perhaps this is also due to how XR experiences lead audiences to gaining clearer perceptions of historical events. The increase of content and context understanding, specific to history learning, is particularly valuable to history museums and historic sites. This is further discussed in the following section about possible outcomes.

Conversely, ineffective XR can create unsuccessful history experiences. *The Guardian* wrote that the Tower of London's VR experience, *The Gunpowder Plot*, encourages audiences to side with either "the crown or the conspirators" (Akbar, 2022). While the topic of political violence is divisive and contemporary, the question coming from this experience seemed "pointless" as many people know how the plot turned out (ibid). A writer for *Time Out* agreed, comparing the experience to a theme-park ride that gives you an "illusion of choice" with no change on the outcome, leaving audiences entertained but not making the most of the conversation which it started (Lukowski, 2023).

## 4. Understanding or Changing Scale

> A good [in-person tour] guide can really illustrate those stories well through his or her words, but often, a sense of scale–whether it's a building or when you're talking about a charge in the Civil War where there are 15 to 20,000 humans running at one another–it's really hard to understand what that meant and what that looked like. So, with augmented reality, we can actually fill a field: how does it look? How might it feel, if we can get people to feel it, to be around thousands of horses with people atop those horses fighting one another, and it happened right there?"
>
> *-Interview with Larry Swiader*

Humans are notoriously bad at understanding scale,[2] and using XR can give visitors an appreciation for just how large the distance between planets is, how small a nanoparticle is, or a more realistic scope of war. Multiple projects in the review used XR as a tool to help visitors understand aspects of scale, including war-focused experiences from American Battlefield Trust, and from the World War I experience from the eyes of a soldier called *War Remains* (Haskins, 2021). The American Museum of Natural History offered a less emotional example of understanding scale with *T. Rex: Skeleton Crew*, in which participants use Viveport VR to build a T. rex skeleton piece by piece, resulting in a fuller understanding of its size before it "transforms into a walking, breathing beast" (Hayden, 2019).

## 5. Inaccessible Sites Made Available

> I try to focus on VR that is not so much making new worlds, but making current worlds accessible."
>
> *-Interview with Kai Frazier, Founder & CEO at Kai XR*

VR is particularly useful in showing inaccessible areas of museums. By the time the COVID-19 pandemic hit, Rijksmuseum, The British Museum, and MOMA are a few that already had virtual and augmented experiences up and running. Other museums created VR access for shows that had not yet opened to the public (and would not for the foreseeable future due to the pandemic restrictions). A museum consultant for the National Galleries of Scotland's *Ray Harryhausen: Titan of Cinema* mobile VR said that the exhibition, newly open yet immediately prohibited to visitors in early in the pandemic, was a promising signifier of museums' ability to "translate'' physical exhibitions to pandemic-era virtual programming (Woody, 2021).

For some potential visitors, a pre-pandemic divide already existed due to inaccessible conditions. In Philadelphia, the Barnes Foundation started offering VR tours to populations who were not visiting the museum (Chinn, 2019) well before COVID-19. Participants at a senior center who had not yet visited the

[2] In a study from 2007, researchers explain that most people lack a "firm grasp on size and scale," as "science education research has identified many areas of conceptual difficulty for learners that are related to size and scale," including chemistry, geography, and even object size (Delgado, et al., 2007).

Barnes became enthusiastic to visit, particularly to see art in person that they had just seen in VR (Chinn, 2019). One stated clearly that the VR experience had made her want to come to the Barnes for the first time (Chinn, 2019).

Along similar lines, the University of Central Florida produced an XR experience called The Virtual UCF Arboretum using a game engine, where 100 hectares of Florida wilderness can be explored in high fidelity, allowing small details of plants and terrain to be perceived virtually (Harrington et al., 2021). Visitors with physical disabilities especially experienced excitement, engagement, and joy from this virtual hike (Harrington et al., 2021).

### 6. Representing Absence

For some exhibitions, the absence of an object or item is a focal point, focused on missing, stolen, removed, or repatriated objects. Representing absence is a different context than timeline shift: XR projects moving in time generally seek to immerse the audience within that time, portraying a wide range of visual and auditory elements to transport the viewer. In contrast, projects representing absence are focused on missing, stolen, removed, or repatriated objects. The absence of those objects is where the narrative lies.

In his article "Exhibiting Absence," Steven Lubar explores museum narratives about absence through multiple examples– the famous missing paintings from the Isabella Stewart Gardner Museum, to missing art and objects seized in war, to colonialist seizures of objects, now repatriated through the Native American Graves Protection and Repatriation Act to their rightful owners (Lubar, 2021).

In another example of absence, the staff at Monticello has long wrestled with whether to create replicas of buildings which were present during Thomas Jefferson's lifetime. Most of the tangible physical traces of enslaved individuals are no longer prominently present at Monticello; the lack of enslaved individuals' quarters erases narratives which should be present.

AR can allow museums to represent without recreating, in order to foreground the absence. At Boston's Isabella Stewart Gardner Museum, an AR experience called *Hacking the Heist* gives users a view of paintings that were cut out of now-empty frames that still hang on the walls (*Hacking the Heist*, n.d.). Created in response to the Museum's realization that visitors were curious about the look of the absent art, this experience "caught the attention of visitors from all over the world who were mesmerized and excited to see the masterpieces that once filled the now empty frames" (*Hacking the Heist*, n.d.).

## What are the possible outcomes from using XR in museums?

Museum professionals have expectations XR might impact their audiences in a variety of ways, especially the following seven outcomes of gaining or experiencing:

1. Content knowledge;
2. Sense of wonder, awe, or magic;

3. Excitement over the novelty of XR;
4. Interest or curiosity in the content;
5. Perception of the museum as up-to-date;
6. Emotional responses to the material; and/or
7. Feeling "there," or a better understanding of a place.

The evidence on XR's ability to achieve these outcomes is mixed. This report's project and literature reviews serve as a starting point for seeking evidence in favor of—or in contradiction to—the above expected outcomes.

While *Tar AR's* primary goal was exploring content knowledge gains, its findings touched on most of these outcomes.

### 1. Gained Content Knowledge

Evidence that visitors increase their learning through XR is mixed. Multiple projects and scholarly papers have found evidence of knowledge gain, others say there was no learning gain. Few of these projects examine whether visitors gain more knowledge from XR in comparison to other potential techniques. Without a control group, it is difficult to determine whether any potential gain is worth the expense of using XR for this purpose.

Participants of the AR experience at La Brea did gain knowledge about the Ice Age version of the ecosystem where they were standing, but *not* more so than those participating in the control variable: a poster communicating the same information as the AR experience (Herrick et al., 2021). Anecdotal knowledge from *Tar AR* and other projects suggests that visitors had a significantly longer engagement time when at individual exhibit elements and when they more closely observed the details. This increased time and focus may be the factors that contribute to learning when it occurs.

Other projects across content domains (science, nature, and history) also demonstrated evidence of learning gains. AR and VR experiences explaining research on immune systems at the North Carolina Museum of Natural Sciences helped visitors (elementary aged through adults) "fill critical knowledge gaps" about molecular evolution (Dornburg, 2022). At an arboretum, participants used information presented by the Mobile AR (MAR) app to physically and verbally identify features of the Arboretum's caves (Zimmerman et al., 2020). Evaluation of Chicago History Museum's *Chicago 00- The 1893 World's Columbian Exposition* found that 80% said they learned new facts from the experience, and one-third could specifically identify historic themes and cultural elements of the experience (McGaughey & Russick, 2021).

While the *Tar AR* project compared AR learning gains to a non-XR control, few of our researched projects compared XR learning gains against other conditions. The VR experience in the *IceCube Neutrino Observatory Exhibit* at the Wisconsin Institute of Discovery conveyed content more effectively than the comparable touch table experience (Tredinnick et al., 2020). Some projects in the literature gave evidence of outcomes with XR, but did not compare to a control state or alternate condition. The

gains described may therefore have been achievable through other means such as through docent interpretation or signage, as the studies referenced are not comparative.

We found multiple examples of visitors who were captivated by the experience, but recalled little of the didactic content knowledge. Specifically, this contrast between immersion and inability to recall content occurred in the examples in which visitors needed to disaggregate the visual experience from the auditory experience. The authors of this report, in several first-hand experiences, saw individuals struggling to process both the visuals and the narration, and ending up blocking out the narration to concentrate on the visuals. As one viewer of Chicago History Museum's *Chicago 00* noted, "I just had to tune out the audio in order to concentrate." When the bulk of the learning content was within the audio, audience members were less able to recall historical themes or elements.

This phenomenon was noted in other projects as well, including the *Tar AR* project, and the *May 4th AR Experience* about the 1970 shooting at Kent State University. A participant of that evaluation said it was "hard to stay interested due to the narrator's delivery," which they described as monotonous (Raber, 2020).

### 2. A Sense of Wonder, Awe, or Magic

> The Rembrandt Peale studio example, sure- that would have been a really cool experience without the AR, but we wanted it to be magical, and it was designed by a magician [David London]. The AR added the magic.
>
> *-Interview with Nancy Proctor, Chief Strategy Officer & Founding Director of The Peale*

Both the blending of reality in AR and the immersion in VR provoke a sense of wonder. Some visitors described it as awe or magic; others were highly intrigued by seeing something differently. *Tar AR* project measured emotions, and analysis showed high engagement in the forms of a 'sense of wonder' and 'excited,' in addition to 'curious' and 'inquisitive.'

Some museums have incorporated the amusement of Instagram and Snapchat filters into their offering. At the Lake Tahoe Environmental Research Center, visitors can take selfies in historic ski clothing while they learn about climate change (Waldman, 2022). Anecdotally, the selfie filters were one of the most popular aspects of the *Tar AR* project.

Recognizing excitement through another lens, the AR experience in the U.S. Holocaust Memorial Museum's *Tower of Faces* (informally referred to as *TowAR)* brought what, in our interview, Future Projects Manager Silvina Fernandez-Duque called "a little pop" of discovery:

> With [*TowAR*], there is a moment of delayed discovery, a little pop, and then also satisfying this urge to learn more about these individual people. I can't imagine doing that in an engaging way that isn't a digital experience.

Michael Haley Goldman, the former Future Projects Director of the U.S. Holocaust Memorial Museum, agreed with Fernandez-Duque:

> Those moments of joy, that colorization, was one of those things that we really only learned about through testing. It was not something that was originally part of the plan. It's that moment of that person looking like [they're in] a modern photograph just for a second. It's such an experientially great moment that it's hard to imagine the project without it.

### 3. Excitement Over the Novelty of XR

For those that have not experienced XR, excitement about simply trying the XR is definitely an outcome, specifically excitement about the experience rather than content. While this interest might be motivating just for the novelty, it can at times also transfer to the content. Facilitators supporting students from a Title One school who were exploring *Lineage*, The Smithsonian National Museum of American History's VR experience about "the history of life on earth," noted that the "kids were so stoked about it" in part because they had not necessarily experienced VR before (Borland et al., 2021). Kai Fraizer, the CEO of digital learning platform *KaiXR,* noted in our interview:

> We're seeing that VR is leading to a lot of other things, like STEM, or confidence... because the kids are excited to come to school and use new tech. I see even impulse control changing: kids having more patience even waiting for a VR headset.

XR in museums can generate such enthusiasm from visitors that they will personally encourage people they know to also attend the experience. For example, all of the teenagers who tested out the final version of *Explore*, an immersive VR experience that encourages a sense of connection to the ocean through virtually scuba diving, enjoyed it so much that they expressed interest in completing other modules should they become available (Carroll & Tambe, 2022).

### 4. Increased Interest or Curiosity in Content

The best technology is transparent enough to allow the content to be the main focus of the experience (Haley Goldman, 2019). Ultimately one goal of many XR projects is to increase awareness of and interest in the subject matter. Research and evaluations into these projects need to determine whether the excitement and interest generated is for the technology alone, or extends to the content. This is especially critical for projects which use the XR experience as a hook to capture interest, leading to a deeper engagement in the surrounding exhibits, content, or interpretation. Here, XR experiences could serve as a lead-in to deeper engagement if that interest is transferable outside of the experience.

The first and last of *Tar AR*'s four studies (Iteration 1 and the RCT) measured interest as an increase shown from pre-test to post-test, in addition to knowledge. The team ran an analysis of qualitative data which showed 4 factors: high engagement, a sense of wonder, discomfort, and disengagement. Within the highly engaged group, curiosity was one of four emotions described (along with interest,

excitement, and inquisitiveness). This group's high engagement statistically significantly predicted learning gains and change in knowledge for all conditions (Nye et al., 2023).

Even when knowledge gains are not measured, XR's capability of encouraging visitors to look more closely can increase their interest in content. Silvina Fernandez-Duque told us in her interview about *TowAR* at the US Holocaust Memorial Museum:

> It's been successful in its intention to keep people in the space longer... without the AR, most people were just walking straight through the space. And so now, having the [AR] experience, they've actually slowed down in an intentional way.

However, other approaches can achieve the same outcome, as in the *IceCube Neutrino Observatory Exhibit.* While the VR experience increased curiosity from users, it was only slightly more of an increase than seen with users of the comparable touch table experience (Tredinnick et al., 2020).

### 5. Perception of the Museum as Up-To-Date

Articles and interviews with museum professionals raised the point that museums are interested in developing XR projects because they believe it will increase perception that the museum is innovative or on top of current trends. This perception was occasionally realized in the literature.

Within the literature review, journalists were less likely to be convinced than the visitors that an XR experience demonstrates the museum is a bellwether of current technology. Multiple media articles covering a variety of AR and VR projects had quotes from visitors that the experience was 'gimmicky' or the experience obscured the art. It is difficult to say whether these were journalists seeking a range of reactions, not indicative of the general perception.

- A reporter for an Australian arts and culture periodical criticized the Australian Center for the Moving Image's VR exhibition *Did You Ask the River* for its dated graphics, describing the installation as "having the look of a 90's Nintendo 64 game with all the functionality issues of an 80's Atari game" (Osborne, 2019).

- A journalist from *The Guardian* reported that The Tower of London's VR experience, *The Gunpowder Plot*, has a lot going for it with a talented live cast and exciting lighting and sound design. But it "does not carry the wow factor" as the plot is underwhelming and the VR technology inconsistent, leading to disappointment and inefficacy for the tour group (Akbar, 2022).

- Another deterrent may be visual limitations, like an AR artist's response to Kiki Smith's *I Am a Wanderer*, who said the mobile VR was "less engaging due to the inability [for the viewer] to get close to the artworks" (The Art Newspaper's XR Panel, 2021).

The need to be seen as innovative and current is frequently derived from a desire to increase public motivation to visit. We could find little to no evidence an XR experience motivates prior non-visitors to

make a visit to the Museum. Waves of past technological advancement, such as mobile phone tours, have not spurred increased visitation, though they may contribute to a positive view of the museum as up-to-date.

### 6. Emotional Responses to The Material

Emotional reactions to XR experiences are often specific to content type: immersive experiences about war or suffering will typically inspire stronger feelings in audiences than an exploration of the size of a blue whale, or immune system research. Many of our interviewees referenced the emotional impact of *Carne y Arena*—an immersive VR and video art experience by Alejandro G. Iñárritu, based on interviews with Mexican and Central American refugees about their life stories. The viewer is situated among a group of people who are led by a coyote[3] across the Mexican border into the U.S. until they are stopped by the border patrol. In this full-immersion experience, one feels the sand, hears the sound of helicopters, sees the blinding spotlight focused on their location. This experience has a clear experiential and emotional goal, as opposed to content learning, and was deemed highly successful in garnering strong emotional responses. Variety Magazine's reviewer described tears flowing when he removed his headset (Gleiberman, 2017).

Other examples demonstrate emotional responses to content at a "visceral, physical level" (Haskins, 2021), eliciting empathy and strong emotions. Writing about *War Remains*, the immersive VR experience about World War I via a soldier's perspective, a reporter for AR Post was moved to tears, noting the experience would be more impactful within the National WWI Museum and Memorial's context than alone in a home gaming space (Haskins, 2021).

In a similar vein, *The May 4th AR Experience* also deals with harm caused by political violence. From a study about the impact of the experience, a respondent noted that it was "powerful and surreal being in the location where the soldiers fired upon the kids" (Raber, 2020).

In *TowAR,* teens praised the United States Holocaust Memorial Museum's mobile app for blending testimonials with images, allowing them to gain a deeper, emotional understanding of the Holocaust and its impact on families (United States Holocaust Memorial Museum, 2018).

Larry Swiader of The American Battlefield Trust said in our interview that historical XR experiences cannot fully convey the original incidents, but when emotions arise, engagement is certainly affected:

> I don't think what we do can help anybody understand what it was really like, so that's not a goal of mine. But I do think that you can understand something about the battle in that way that

[3] In this context, the colloquial term *coyote* refers to a person who transports people into the United States over the Mexico-U.S. border for a fee. According to *Wikipedia*, "the proportion of migrants who hire coyotes has increased drastically as a result of intensified surveillance along the border" since the 1990s (2023, April 17. https://en.wikipedia.org/wiki/Coyote_(person).)

> you couldn't before. I think it does pull on you emotionally, and that emotional pull allows you to pay attention in a way that's important.

In addition to feelings about historic and political conflict, XR can also inspire emotional responses to environmental harm. At the Australian Centre for the Moving Image, a reviewer described the environmentalist VR experience *Did You Ask the River?* as a "bittersweet" embodiment of the consequences of one's actions, reinforced by its placement of a mirror before the user, an "uncanny experience of self-witnessing" (Munro, 2019).

On the other hand, a learning experience as seemingly non-emotional as *Tar AR* also brought feelings to the playing field, which affected the learning gains of the study participants. Across all three *Tar AR* studies, one of the most consistent findings was that self-reported emotions after the experience were a significant and strong predictor of pre-post learning gains. Responses such as interest and curiosity (discussed above in Increased Interest or Curiosity in Content) and the feeling of excitement predicted learning, even more so than self-reported interest in either science or in augmented reality. Conversely, learning gains were lower when visitors reported frustration or struggled with the experience, even when levels of frustration were small. While this finding makes intuitive sense, the structure of the study did not make it possible to determine *how much* excitement or frustration affected learning gains, as both could be the result of shared causes or unknown variables.

Perhaps less common, XR can also deepen feelings about more abstract content, even when harm or conflict are not topics in play. Describing Laurie Anderson and Hsin-Chien Huang's VR journey to a fictional moon, an *Art in America* journalist wrote of *To The Moon*:

> Sealed inside the private animation of my headset, near a handful of others seated on low stools, I felt a sense of astonishment followed by swift grief. On this trip to the moon, we are not going home—at least, not by the way we came (Miller, 2019).

### 7. Feeling "There," or a Better Understanding of a Place

Harder to quantify (or even describe) was the outcome of feeling a deeper connection to—or better understanding of—a place. However, this outcome was regularly mentioned by interviewees and study participants. Visitors often report that they looked at a place differently or connected to a place differently after XR experiences. In *Tar AR*, participants noted how the land they were standing on was warmer and wetter during the Ice Age than they previously understood (Herrick et al., 2021).

There are many examples of other place-augmenting experiences within a range of sites. In the realm of history, the *Chicago 00* experience of the 1933 World's Fair delivered a new depth of understanding of the city that the visitors were in. In experiencing the Sky Ride, "the novelty of that moment and the intensity of 'being there' led to a form of embodiment experienced by the visitors" (McGaughey & Russick, 2021).

Secondly, two young adults testing *The May 4th AR Experience* agreed that the app allowed them a deeper understanding of the context around their campus's buildings at Kent State, like the Taylor Hall Pagoda (Raber, 2020).

XR about war also brought visitors there. A journalist writing about the Japanese American National Museum's *Be Here: 1942* described the emotional power of the mobile AR experience: "To go and see [the courtyard] filled with these kinds of apparitions is powerful. You realize that this was done to these people, right here. It's almost bearing witness to history in a different way" (Huang, 2022). The *Gettysburg Battlefield AR App* (affiliated with the American Battlefield Trust) immerses users in combat, bringing them an intimate, environmental understanding of the Civil War by combining the action with testimonies from soldiers, locals, and journalists who lived the experience (Melnick, 2020).

For science, adult and teen respondents to the study about *Explore*, the VR experience that immerses users in a digitized experience of scuba diving, said they were left with "feeling a connection to a place I hadn't been before" (Carroll & Tambe, 2022). This connection led some to new understandings of climate change. One teen remarked, "I think you might feel more interested, connected and engaged by having some firsthand experience with the ocean" (Carroll & Tambe, 2022).

## Considerations in Implementing XR

> I read in a tweet from Mike Jones in Australia about how, while VR has been the promised future of museums for about 20 years, we have never realized that potential. But we as museum people always see it as the next thing. Tech partnerships will not be reliable! Individual museums might create a great AR program, but it might not be widely adopted into the future. It may continue to be used for experimentation, or used for accessibility, but doing it for pointed ways throughout the museum field may not last.
>
> *-Interview with Suse Anderson, Assistant Professor of Museum Studies at The George Washington University (referencing Jones, 2022)*

Our interviews and reviews of the literature contained considerations for museum professionals when deciding whether or not to implement it at their institutions. Cost of development was sometimes mentioned, though cost of maintenance was cited more frequently as under-budgeted. Changes or upgrades to the hardware or software, including frequent upgrades to phone-based operating systems, means any long-running experience will need to be adjusted or rebuilt over its lifespan. As Michael Haley Goldman explained:

> It's very easy for institutions to fall into thinking, "Okay, we're just gonna build something, then not pay attention to it, and when things break, we're going to fix it. We really want these experiences to be self-sufficient; we don't think of them as active projects for staff." That's not practical. Even the changes in monitors alone are really complicated over time.

This precariousness of the technology means that museums and cultural institutions are reliant on large software companies. When those companies change the software, the implications for such museum experiences can be significant. Ian Garrett, the Artistic Producer & Designer at Toasterlab, related how he discovered that YouTube had changed the feature on which all of his bespoke content relied: in the middle of a presentation of his new app. Due to this precariousness and the cost of maintenance, some museums have elected to use off-the-shelf software or platforms, where other individuals are responsible for the stability of the application or experience. Other projects focused on a mobile-web foundation, which made their efforts less reliant on software or hardware.

Several interviewees noted how there is a lack of competition for production of VR hardware. This both increases the dependency on technology companies, specifically Meta, and stifles the development of other options. Kai Frazier explained in our interview:

> The most popular headset is the Oculus series, Oculus Quest 1, Quest 2, all owned by Meta. The headset is taking their biometric data into it. So when we put kids in this headset, we know that we are offering up their data in ways that [our customers] necessarily would not have agreed to. We try to, in a way, not to scare our customers, but just let them be very aware about that.

Frazier raises questions not just about the dependency on Meta for VR, but on how Meta is using the data they gather. Meta has revealed the internal cameras' ability to gather nonverbal expressions and gestures, though the amount and types of data the headset is gathering may not be public knowledge (Johnson, 2022).

As noted in the outcomes section above, some VR applications in museums led to strong emotional responses, a deeper connection to a place, or increased interest in content. Museum staff need to weigh these potential outcomes against the cost of development and maintenance. Interviewees also noted that some of the most successful VR experiences required considerable personnel and other supports in order to be successful. Iñárritu's *Carne y Arena* was a heavily-staffed experience that could only accommodate a few individuals at a time; scaling a similar experience to museum visitors would be challenging. Simpler VR installations also required significant staffing to show individuals how to use the headset, monitor for signs of dizziness or nausea, and clean headsets after use, at minimum.

In addition to staffing, scaffolding learning is a commonly-cited requirement for a successful museum XR experience in both the interviews and literature review. Kai Frazier noted that while the VR field-trip experiences for students are highly successful, the VR does not stand on its own; it is a component of a set of curriculum and discussions integrating to support learning. She explained the need for scaffolding:

> Then we had another group where they watched it, we hit pause, they would have to do something like build a coral reef. And then we would go back and pause. What I found is that sometimes all the interactivity takes away from what they're comprehending. So when their brain is too much, they can't do it. So the way I do my experiences, there are 360 videos and then there's an activity afterwards. Especially for empathy building, for some of the trauma I'm talking about, just listening is not enough.

In addition to the cognitive barriers, VR headsets can be physically challenging or uncomfortable. Some users of the *Tar AR* headsets felt they were bulky, hot, or unsafe (Nye et al., 2023). While the headset provided a range of vision in all directions and, with that, deeper immersion than the phone-based AR, these discomforts may have contributed to the statistically significant lower knowledge gain from the headset compared to the handheld phone (Nye et al., 2023). Kai Frazier noted motion-sickness, germ-sharing, as well as hair size or style can also be deterrents to headsets, while handheld devices receive none of these complaints. These barriers lead her to only use web-based experiences:

> We're device-agnostic. That's a big deal. The reason why the VR that I do is so great is because it will work on any web browser, including a laptop or smartphone, a tablet. Although it may not be a fully immersive experience, it will be a 360 experience. They can take it, move the phone up and down, kind of see it around them. And this is great because the VR headsets are only for ages 13 and over. So what do you do when kids want to do a lot of this stuff, where a tablet may be that first touchpoint pathway to even seeing in a spatial 360 representation?

## Future States

> I feel like that's where we are with VR, that it's got a lot of affordances, but we just need more time to really figure out how to use it well. And I think the best examples that I've seen of VR and AR have been in context where there's a lot of physical support as well. They're not purely digital experiences.
>
> *-Interview with Nancy Proctor*

All of the sources with whom we worked noted the quickly evolving environment for XR. Larry Swiader noted, “I don't think we're past the novelty stage in AR in museums. We may be in other sectors. Healthcare is one of those where I think we're getting past it, where it's more acceptable to use AR and VR alike, especially for simulation.”

Experts looking at the future of AR and VR in museums were focused on several key developments, including the ones mentioned above, such as lack of competition for headset production, privacy issues, and stability in platforms. They were also tracking how XR is evolving to be more social, such as in shared AR experiences. Larry Swiader shared this example:

> 8th Wall, which is one of the companies that makes a platform available to deliver augmented reality, now bought by Niantic, which owns *Pokémon*, they are releasing right now a functionality that they call Lightship, which allows people to pin augmented reality to locations. And you can go ahead and scan those, and once a location's scanned into the database, people can happen upon them, which is interesting!

Shared social experiences were noted as a boon from multiple AR installations, including *Tar AR*, where excitement over the experience and the content was expressed through sharing with others within their social group. The developers of the *Krishna* exhibition choose AR over VR specifically to allow

conversation within social groups. Applications and formats that increase the ability to share and discuss are also evolving, and with new advances, museums may find XR to be increasingly attractive.

One visitor who rated the *Krishna* exhibition as 'outstanding' in its summative study commented: "Multi-interactive experiences showed such an amazing and new way to exhibit objects. It shows how the future of museums will evolve."

## Conclusions

Our museum expert interviews and literature review showed considerable experimentation with AR and VR within museums. Historical sites and museums, outdoor sites, and previously inaccessible sites were seen as the most successful contexts for XR. Experts and literature described XR as particularly useful to show timeline shift, scale change, or the representation of absence.

In examining the outcomes of using XR, there was evidence that XR can promote content knowledge gain, but not necessarily more so than other methods. La Brea's *Tar AR* project found that learning happened in all test conditions: both the AR and control states (Nye et al., 2023). However, the AR conditions in this project were the only ones which led to higher engagement (curiosity, interest, excitement, and inquisition), and these are valuable to the Museum beyond the promise of audiences gaining content knowledge. The excitement and mystery of XR, as its technological state and popularity exist currently, can draw visitors into the museum and deepen their overall experience regardless of–or in addition to–learning gains. The outcomes of a sense of wonder, content interest and curiosity, and a deeper sense of place appeared in multiple projects reviews. XR, particularly VR, also was able to bring about deep emotional responses.

Museum professionals considering XR experiences should weigh the potential outcomes and other considerations, specifically cost, dependency on specific hardware and software, physical comfort, privacy, and need to embed the XR experience in a larger contextual experience. The field can expect that XR is not a flash-in-the-pan trend, but it is, as of yet, still evolving.

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## Appendix A

**List of Projects Reviewed**

| **Name of Project** (hyperlinked 4/17/23) | **Lead Institution** | **Associated Individuals** (if known) | **Year Began** (approx) | **Info Source** |
|---|---|---|---|---|
| [AR]T Central Park | Apple | | 2019 | The New York Times |
| [AR]T Museum | Cuseum | Brandon Ciecko, Dan Sullivan, Maria Betancur | 2018 | Web search |
| Accessible Dynamic Informal STEM Learning for Deaf and Hard-of-Hearing | Rochester Institute of Technology | Chia Shen, Wendy Dannels | 2018 | NSF Award Search |
| Advancing Ocean Literacy through Immersive Virtual Reality | The Leland Stanford Junior University | Robert Russell, Becky Carroll, Pam Tambe, Jeremy Ballenson | 2019 | InformalScience.org |
| AMNH T. Rex VR | American Museum of Natural History | | 2019 | Rachel Pelegrino |
| Arcadia Earth | Arcadia Earth | Valentino Vettori, Christiano Quieti, Bryan Verona, Michael Pollack, Andrea Venturelli, Nour Seikaly, Natasha Berg | 2022 | HG&Co project |
| Augmenting Museum Visits: Guiding Families to Share in the Learning | Lawrence Hall of Science | Mac (Matthew) Cannady | 2018 | InformalScience.org |
| Australian Museum VR Tours | Australian Museum | | | Suse Anderson |
| Barnes tours | Barnes Foundation | Valerie Gay | 2019 | John Gordy |
| Bayi Gardiya (Singing Desert) | Australian Center for the Moving Image | Christian Thompson | 2019 | Suse Anderson |
| BeHere 1942 | Japanese American National Museum | | 2022 | Matt Davis |

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|---|---|---|---|---|
| Broadening Participation in Informal STEM Learning for Autistic Learners and Others through Virtual Reality | TERC, Inc. | Robert Russell, Teon Edwards | 2020 | NSF Award Search |
| ButtARfly | Cooper Hewitt (Smithsonian Institution) | Jonathan Lee, Miriam Langer, Rianne Trujillo, Lauren Addario | 2021 | HG&Co project |
| Cahokia AR Tour | Cahokia Mounds Museum Society | Jack Kerber | 2020 | InformalScience.org |
| CAREER: Understanding Evolutionary Responses to Climate Change Across Space and Time | Regents of the University of California | Samuel Scheiner, Ian Wang | 2019 | NSF Award Search |
| Carnival of Fantasies | National Palace Museum, Taiwan | | 2020 | Bruce Wyman |
| CHAR: Cultural Heritage Augmented Reality Apps | University of Toronto | Liron Efrat | 2021 | Bruce Wyman |
| Chicago 00: The 1893 World's Columbian Exposition | Chicago History Museum | Geoffrey Alan Rhodes, John Russick | 2000 | Bruce Wyman |
| Chroma AR: Ancient Sculpture in Color | The Metropolitan Museum of Art | | | Matt Tarr |
| Civil War 1864 | American Battlefield Trust | | 2019 | Bruce Wyman |
| Critical Distance | National Museum of Natural History (Smithsonian Institution) | | 2021 | Web search |
| Did You Ask the River? | Australian Center for the Moving Image | Joan Ross, Dr. Josh Harle | 2019 | Suse Anderson |
| Doorways into Open Access | Cooper Hewitt (Smithsonian Institution) | Abigail Honor, Jean-Pierre Dufresne | 2021 | HG&Co project |

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|---|---|---|---|---|
| Empowering Informal Educators to Prepare Future Generations in Wireless Radio Communications with Mobile Resources | Concord Consortium | Toni Dancstep, Sherry Hsi | 2020 | NSF Award Search |
| Epiphytes | Australian Center for the Moving Image | Tully Arnot, Dr Monica Gagliano | 2022 | Suse Anderson |
| Exploring the Universe from Antarctica- An Informal STEM Polar Research Exhibit | University of Wisconsin-Madison | Ross Tredinnick, Rebecca Cors, James Madsen, David Gagnon, Silvia Bravo-Gallart, Bryce Sprecher, Kevin Ponto | 2018 | InformalScience.org |
| Free & Equal | Free & Equal | Gregory Downs, Eric Foner, Kate Masur, Melissa N. Stuckey, Tara Y. White, Daisy Martin, J. Brent Morris, Lawrence S. Rowland, Stephen R. Wise | 2021 | Patricia Brooks |
| Game Changers exhibition: A sports exhibition and research study to encourage inventive identity development and broaden participation in STEM innovation | Smithsonian Institution | Toni Dancstep, Monica Smith | 2020 | NSF Award Search |
| Gettysburg AR Experience | American Battlefield Trust | Lawrence Swiader | 2020 | Bruce Wyman |
| GO! NFT: blending urban and digital arts | Game Over Berlin | | 2022 | Web search |
| Google Arts and Culture: Pocket Gallery | The Getty Museum | | 2021 | Web search |
| Gunpowder Plot | Tower of London | Hannah Price, Danny Robins, Tim McQuillen-Wright, Adrienne Quarterly, Simon Reveley | 2022 | Jim Richardson |

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|---|---|---|---|---|
| Hacking the Heist | Cuseum | | 2018 | Kate Haley Goldman |
| Hidden No More: Shedding Light on Science Stories in the Shadows | University of North Carolina at Chapel Hill | Robert Russell, Todd Boyette | 2019 | NSF Award Search |
| I Am a Scientist: Moving African American youth beyond participating in STEM activities to committing to a STEM identity | Clemson University | Adrienne Dixson, Harrison Pinckney | 2019 | NSF Award Search |
| Immersive Augmented Reality Landscape Viewer for Public Space Deployment | Perceptoscope | Rajesh Mehta, Ben Sax | 2019 | NSF Award Search |
| Insects 3D | Okinawa Institute of Science and Technology | Eli M. Sarnat, Francisco Hita Garcia, Kenneth Dudley, Cong Liu, Georg Fischer, Evan Economo | 2019 | Oxford Academic |
| Kent State May 4th | Kent State University | Richard E. Ferdig, Robert Clements, Enrico Gandolfi, Cheng Chang Lu, Annette Kratcoski | 2020 | Patricia Brooks |
| Laurie Anderson: To the Moon | Massachusetts Museum of Contemporary Art (MASS MoCA) | | 2022 | John Gordy |
| Lessons from museums: impacts of urbanization on biodiversity and the importance of natural history collections | North Carolina State University | Daniel Marenda, Selina Ruzi | 2019 | NSF Award Search |
| Lessons of Auschwitz | Victory Pages | Denis Semionov, Peter Theremin | 2020 | Corey Timpson |
| Librarium | Librarium | Duane Mathes, Jim Bradbury, Annie Morley, Nick Gutschow | | VR Scout |

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|---|---|---|---|---|
| LINEAGE: A Cross-Platform Learning Experience Exploring the History of Life on Earth | National Museum of American History (Smithsonian Institution) | Kristen Pederson, Jennifer Borland, Amy Bolton, Michael Rosenfeld, Fritz Bergman, Marion LeVoyer, Gale Robertson | 2021 | InformalScience.org |
| MoMAR | MoMAR | Monique Baltzer, David Lobser | 2019 | The Architect's Newspaper |
| Museum Alive | Alchemy Immersive | | 2021 | Web search |
| Museum of Other Realities | Museum of Other Realities | Colin Northway, Robin Stethem, Stephen Gray, Lindsay Jorgensen | 2017 | VR Scout |
| Norton Art + | Norton Museum of Art | | 2021 | LocalProjects.com |
| Ray Harryhausen: Titan of Cinema | The National Galleries of Scotland | | 2020 | Bruce Wyman |
| RETTL: Facilitating socially constructed learning through a shared, mobile-based virtual reality platform in informal learning settings | Virginia Tech University | Fengfeng Ke, Sang Won Lee | 2021 | NSF Award Search |
| Revealing Krishna | Cleveland Museum of Art | Jane Alexander, Sonya Rhie Mace, George P. Bickford, Andrew Gutierrez | 2021 | Corey Timpson |
| Revivre | The French National Museum of Natural History | | 2021 | Web search |
| SDMA AR App | San Diego Museum of Art | | 2021 | Web search |
| Seeing Picasso at PACE Gallery in Palo Alto | Pace Gallery in Palo Alto (permanently closed) | | 2019 | LocalProjects.com |
| Seeing the Invisible | The Eden Project | | 2021 | Web search |

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| Seeing the World through a Mathematical Lens: A Place-Based Mobile App for Creating Math Walks | Southern Methodist University | Leilah Lyons, Candace Walkington | 2021 | NSF Award Search |
| Slavery at Monticello Mobile Guide | Thomas Jefferson's Monticello | | | Web search |
| Smart Science Exhibits: Enhancing STEM Learning through Sustained Use of Mixed-Reality in Multiple Informal Learning Spaces | Carnegie Mellon University | Robert Russell, Nesra Yannier | 2020 | NSF Award Search |
| Symbiosis | Portland Art Museum: Center for an Untold Tomorrow | Marcel van Brakel, Mark Meeuwenoord, Corine Meijers, Marieke Nooren | 2022 | Bruce Wyman |
| Symphony | La Caixa Foundation | | 2020 | Bruce Wyman |
| Teaching Human Motion at Population Scale | The Research Foundation for SUNY | Robert Russell, Gary Saulnier | 2018 | NSF Award Search |
| The Academy Museum AR Tools | Academy Museum of Motion Pictures | | 2022 | John Gordy |
| The Blue Whales Project: Engaging audiences in adaptation related science content through a giant screen film and educational activities in science centers and rural libraries | California Science Center Foundation | Sandra Welch, Charles Copczak | 2021 | NSF Award Search |
| The Henry Ford Connect | The Henry Ford Museum | | | Kate Haley Goldman |
| The Virtual UCF Arboretum | University of Central Florida | Maria C. R. Harrington, Patrick Bohlen, Zachary Bledsoe, James Miller | 2016 | Bruce Wyman |

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| Time Travel • Hong Kong | The Chinese University of Hong Kong Art Museum | | 2021 | Bruce Wyman |
| Tracing Paint | Pollock-Krasner House and Study Center | Helen Harrison, David Gochfeld, Lisa Lokshina | 2020 | Bruce Wyman |
| Transforming Outdoor Places into Learning Spaces | Penn State University | Chia Shen, Heather Zimmerman | 2018 | NSF Award Search |
| Understanding the molecular diversification of self-recognition through ray-finned fish innate immune receptor families | Friends of the Museum, North Carolina Museum of Natural Sciences | Joanna Shisler, Alex Dornburg | 2018 | NSF Award Search |
| Urban Archive NYC | Urban Archive | Ben Smyth, Brigid Harmon, Isaac Womack, Katie Smillie, Parker Limon, Tim Bradley | 2016 | Web search |
| Using media and technology to advance public awareness of research on microscopic larvae in the deep ocean | University of Oregon | Sandra Welch, Craig Young | 2022 | NSF Award Search |
| Utilizing the Library System and Virtual Reality Learning Experiences To Engage Rural and LatinX Communities in Polar Research | University of Wisconsin | Arlene de Strulle, Kevin Ponto | 2021 | NSF Award Search |
| War Remains | National WWI Museum and Memorial | Brandon Oldenburg | 2020 | Matt Davis |

## Appendix B

**List of Interviewees**

1. Jane Alexander: Chief Digital Information Officer at The Cleveland Museum of Art. December 2, 2022.
2. Suse Anderson: Assistant Professor of Museum Studies at The George Washington University. November 18, 2022.
3. Silvina Fernandez-Duque: Future Projects Manager at the U.S. Holocaust Memorial Museum. October 28, 2022.
4. Nick Fox-Gieg: XR Developer and Animator at Nick Fox-Gieg Animation. October 28, 2022.
5. Kai Frazier: Founder & CEO at Kai XR. November 8, 2022.
6. Ian Garrett: Artistic Producer & Designer at Toasterlab. November 8, 2022.
7. Michael Haley Goldman: Former Director of Future Projects at the U.S. Holocaust Memorial Museum. November 14, 2022.
8. Nancy Proctor: Chief Strategy Officer & Founding Director of The Peale. October 12, 2022.
9. Ed Rodley: Co-founder & Principal of The Experience Alchemists. September 23, 2022.
10. Larry Swiader: Chief Digital Officer at American Battlefield Trust. October 28, 2022.
11. Corey Timpson: Principal of Corey Timpson Design Inc. and Chair of the AAM Media & Technology Professional Network. September 26, 2022.

## Appendix C

List of Papers Reviewed


1. Alexander, J., Wienke, L., & Tiongson, P. (2017). Removing the barriers of Gallery One: a new approach to integrating art, interpretation, and technology. *MW17: MW 2017.* Published February 16, 2017. Retrieved from https://mw17.mwconf.org/paper/removing-the-barriers-of-gallery-one-a-new-approach-to-integrating-art-interpretation-and-technology/

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10. Harrington, M. C., Bledsoe, Z., Jones, C., Miller, J., & Pring, T. (2021). Designing a virtual arboretum as an immersive, multimodal, interactive, data visualization virtual field trip. *Multimodal Technologies and Interaction*, *5*(4), 18. https://doi.org/10.3390/mti5040018

11. Harrington, M. C., Tatzgern, M., Langer, T., & Wenzel, J. W. (2019). Augmented reality brings the real world into natural history dioramas with data visualizations and bioacoustics at the Carnegie Museum of Natural History. *Curator: The Museum Journal*, *62*(2), 177-193. https://onlinelibrary.wiley.com/doi/10.1111/cura.12308

12. Kassim, M. H., Mohamed Eshaq, A. R., & Woods, P. C. (2019). Mobile augmented reality: An alternative way toward museum visitors' experience. *International Journal of Recent Technology and Engineering*, *8*(2S8), 1420-1425. https://doi.org/10.35940/ijrte.B1077.0882S819

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15. Marenda, D. & Ruzi, S. (2022). NSF Postdoctoral Fellowship in Biology FY 2019: Lessons from museums: impacts of urbanization on biodiversity and the importance of natural history collections. *National Science Foundation*; North Carolina State University Insect Museum; Wake, Durham and Chatham counties in North Carolina.

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